Review of the Current Understanding of Hydrogen Jet Fires and the Potential Effect on PFP Performance

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The fast-developing energy transition, with a target of net-zero greenhouse gas emissions, will include a significant expansion in the use of hydrogen. The roles for hydrogen being considered include energy transportation and storage, land transport, maritime propulsion, domestic heating and 'hard to de-carbonise' industry. In gaseous form, due to its low density, hydrogen tends to be stored at high pressure, often measured in 100s of bar, though the pressure range will depend on the application.

As with hydrocarbon fuels, if an accidental release of pressurised hydrogen occurs, there is the potential for a jet fire. As the scale of hydrogen deployment grows, there will undoubtedly be the need to protect critical structures and equipment using PFP. It is therefore important to understand if the performance of current PFP materials in hydrogen jet fires will be comparable to that in a hydrocarbon jet fire.

This review was produced in the context of the authors principal interest being large scale jet fires where PFP might be required. A comparison of the high pressure gaseous hydrogen releases and jet fires with natural gas and methane has been undertaken and shows that like-for-like the external flame characteristics (flame length, thermal radiation) are not significantly different. If the release is transient (i.e. from an isolated inventory) a hydrogen jet fire will have a duration of about one third of a like-for-like methane/natural gas jet fire due to the higher volumetric outflow in the case of hydrogen. Internal flame characteristics show hydrogen jet fire flame temperatures are greater than those in methane/natural gas jet fires and suggests that the convective thermal flux to an object in the flame may be higher in the case of hydrogen compared to methane/natural gas.

With respect to the possible effects on PFP materials, the hotter flame temperature for a fully developed hydrogen jet fire has potential to cause greater erosion of reactive PFP materials in particular close to the point of impact. Further assessment of the flame temperature and convective and total heat flux within high pressure hydrogen flames would allow a better comparison with other hydrocarbons and provide better insight on the potential impact on PFP.

Keywords: Hydrogen, Passive Fire Protection, Jet Fire

Introduction

The fast-developing energy transition, with a target of net-zero greenhouse gas emissions, will include a significant expansion in the use of hydrogen. The roles for hydrogen being considered include energy transportation and storage, land transport, maritime propulsion, domestic heating and 'hard to de-carbonise' industry. Even if this is only partially realised, there will be a considerable growth in hydrogen facilities for production, distribution and utilisation.

Hydrogen can be stored in gaseous and liquid form. In gaseous form, due to its low density, it tends to be stored at high pressure, often measured in 100s of bar, though the pressure range will depend on the application. If stored as liquid, the hydrogen will be vaporised prior to use. In all applications of hydrogen in the energy transition therefore, pressurised gaseous hydrogen will be present.

As with hydrocarbon fuels, if an accidental release of pressurised hydrogen occurs, there is the potential for a jet fire. As the scale of hydrogen deployment grows, there will undoubtedly be the need to protect critical structures and equipment using Passive Fire Protection (PFP). It is therefore important to understand if the performance of current PFP materials in hydrogen jet fires will be comparable to that in a hydrocarbon jet fire.

This paper provides a comparison of gaseous hydrogen and hydrocarbon jet fires in order to understand better the potential impact of hydrogen jet fires on PFP performance. This assessment is for gaseous hydrogen releases only and information from both experimental studies and jet fire modelling have been considered.

Objective

The objective of the paper has been to determine if current PFP materials and testing methodologies are likely to be adequate for hydrogen jet fires. To do this we must first understand the similarities and differences between hydrogen and hydrocarbon release scenarios and then assess how this might affect the properties of a jet fire. The uncertainties and gaps in knowledge need to be identified, particularly in terms of how this might affect PFP performance.

Achieving this objective will allow the gaps to be addressed and allow it to be determined if the standard fire testing of PFP materials needs to be changed to demonstrate PFP performance against hydrogen jet fires.

Methodology

The initial step is a literature review of the current understanding of high pressure gaseous hydrogen releases compared to hydrocarbon jet fires, primarily methane or natural gas. Analysis is then conducted and as a starting point, in order to make the comparison 'like-for-like', the primary assessment basis is to compare releases from the same hole size in systems at the same pressure and with the same volume in terms of vessels and pipework. Comparison is made between hydrogen and methane/natural gas as there is already some understanding of the differences between methane/natural gas and other hydrocarbons.

Consideration is then made on the impact of hydrogen and natural gas fires on PFP and the potential for the current standard jet fire (ISO 22899-1:2021) test to apply to hydrogen releases. It is recognised that current PFP testing methodologies are carried out using a propane jet and it is therefore being assumed in the comparison made here that the test adequately indicates PFP performance in a natural gas jet fire. Key gaps in understanding that might have an influence on PFP performance have been identified and compared with current industry guidance and testing. This includes comment on the representation of large scale natural gas and hydrogen jet fires by a smaller scale propane test.

Literature

Historically jet fire hazards have tended to be most prevalent in the Oil & Gas industries and have related to the accidental release of pressurized hydrocarbons. Hydrocarbon jet fires of have been investigated extensively. For example, large scale releases of natural gas and LPG (Bennet 1991), jet fire releases of crude oil, gas and water (Hankinson 2007), (Evans 2000), the thermal impact of jet fires on structures (Cowley 1991), the ability of general area and dedicated water deluges to protect against impinged jet fires (Hankinson 2004) , and the response of PFP (Shirvill 1992, and OTO 95 477).

The general outcomes of the tests have been reported extensively and are available in Oil & Gas industrial guidance (FABIG TN13 2014, Oil & Gas UK 2018), scientific journals (Lowesmith 2007) and in reviews specific to the PFP industry (Bradley 2017).

Hydrogen fires are interesting in that although they have been studied extensively at small scale there is little published data of large scale releases that are comparable to those studied in hydrocarbon jet fire research and where fire proofing may be required. Some reported mass flowrates of relevance are: Mogi 2009, up to 100g/s, Schefer 2006 and Schefer 2007 up to 360g/s, Proust 2011 up to 160g/s, Immamura 2008 up to 10g/s. Hydrogen was stored in relatively small volumes and released through orifices of ranging from 0.1mm dimeter to 5.08mm. It is of course interesting but also clearly indicative of a measure of similarity between choked flames that despite their varying release pressures and orifice sizes the ratios of flame width to flame length were all between 0.167 and 0.18

The external hazards of a jet fire are largely governed by the flame size, characterised by the flame length, and the radiative properties of the fire. For structures inside the jet fire, the convective and radiative thermal loading and gas velocities are particularly relevant. Considering length of the jet flame first, Mogi 2009 found the length of the resultant jet flame fit the relationship $\boldsymbol{L_f = 20.3\,\dot{m}^{0.53}}$, whilst Immamura 2008 found $\boldsymbol{L_f = 19.9\,\dot{m}^{0.51}}$. These both are functionally equivalent to the approach taken in FABIG TN13 2014 where the length of a wide range of hydrocarbon jet flames is correlated against $\boldsymbol{L_f = 2.9\,Q^{0.37}}$, and where Q = jet fire power is defined as mass flow rate x the calorific value of the fuel. The conversion from mass flow rate to jet flame power does not appear to be particularly important where hydrocarbons jet flames are concerned because their calorific values are very similar, but as shown later in this note, converting to jet flame power provides a better fit when comparing hydrogen and hydrocarbons.

Schefer 2006 and Schefer 2007 also looked at correlating jet fire flame length against release conditions but plotted flame length against a modified Froude number. The approach worked quite well, though less well at the higher release flows (also discussed by Molkov 2013). Assessment of the figures published by Schefer 2006 and Schefer 2007 has allowed a curve fit flame length against mass flow rate for a limited set of data using the $\boldsymbol{L_f = A\,\dot{m}^b}$ form from above. The curve fits have been included in our flame length assessments discussed later.

Bradley 2016 have proposed a novel non-dimensional grouping which they showed can be correlated against non-dimensional flame heights. This is particularly interesting because it was applied against both hydrogen and hydrocarbon data, at a huge range of release conditions (from pool fires through to jet fires), and also because it was constructed from well defined combustion properties such as laminar burning velocity. If more large scale hydrogen fire data becomes available we intend to investigate this later.

The largest ignited hydrogen jet fire releases identified were conducted at DNV Spadeadam from large capacity onsite gas storage tanks. There were 1kg/s and 7.5kg/s respectively and are summarised in Rian 2019. The flame lengths are discussed in the following sections however it was reported that the fraction of jet fire energy released as radiation was 0.12 and 0.19. Due to an absence of carbon, hydrogen jet fires are not particularly luminous however the measured radiative fraction of 0.19 is above the value quoted in FABIG TN13 2014 for large scale natural gas jet fires. Schefer 2006 and Schefer 2007 describe hydrogen jet fires as having a radiative fraction of about half that of natural gas at a comparable size but also shows that the fraction of heat radiated increases as outflow rate gets bigger. Proust 2011 shows the fraction of energy radiated from a hydrogen jet fire on a 1mm orifice to be about 0.05, but then between 0.1 and 0.15 on 2mm and 3mm orifices (mass flow rates up to a maximum of approx. 0.16kg/s.

There is very limited data available for the internal characteristics of a large scale hydrogen jet fire.

Assessment Basis

The factors considered in the comparison and forming the basis for the assessment are detailed in Table 1.

Table 1: Factors Forming the Basis of the Assessment

Factor	Description
Outflow	The rate at which the gas escapes through a hole in the pressurised system, measured by mass, volume or total combustion energy.
Flame length	Expected flame lengths and how these are measured/ characterised. This includes consideration of flame lift off. Experimentally flame length will often be defined as from the release orifice to the visible extent of the flame, although in modelling predictions it is normally to a particular temperature contour.
Flame stability	The conditions under which a flame can stabilise on a free jet release.
Fraction of heat radiated	The proportion of the available combustion energy in the released gas that is then emitted as radiant energy.
Gas velocities/densities	Velocities and associated densities within the jet flame
Radiative heat flux	The thermal flux (kWm^{-2}) that an object engulfed in the flame receives as thermal radiation.
Convective heat flux	The thermal flux (kWm^{-2}) that an object engulfed in the flame receives from convective flow.
PFP performance	The effect of any differences or uncertainties in the properties of hydrogen and methane jet fires on PFP performance.

Comparison of Properties

Outflow

Release Rate and Duration

This assessment only considers sonic gaseous releases, where the internal pressure is sufficiently high to accelerate gases to their speed of sound as they pass through a release orifice. Because the speed of sound is a limiting factor at the orifice, the gases pass through the orifice at higher than ambient pressure, continuing to expand in the external atmosphere resulting in a pseudo-orifice a little way downstream of the physical orifice as described by Birch 1984. This flow behaviour is often referred to as choked flow.

As choked flow occurs at a pressure just over 1.8bara, in reality all gas releases where application of PFP is considered would involve choked flow.

For hydrogen and methane, sonic mass outflow through a defined hole in a pressure system can be calculated by equation (1).

$$\dot{m} = C_d \frac{A p_0}{\sqrt{\gamma R T}} \gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{1}$$

Where:

$\dot{m}$ is the mass release rate (kg/s)

C_d is the discharge coefficient

A is the area of the release orifice (m^2)

p_0 is the absolute upstream pressure (Pa)

R is the individual gas constant (J/kg/K)

T is the absolute temperature of the upstream gas (K)

γ is the specific heat ratio

Equation (1) is a variant of the choked flow equation. With all else being equal and an invariant discharge coefficient, equation (1) shows that the choked mass flow rate of a given gas through a circular orifice is directly proportional to the upstream pressure, and inversely proportional to the square root of the upstream temperature of that gas. Recognising that mass flow rate is also inversely proportional to the square root of the individual gas constant R which is equal to $R_{universal}/M$, it is also seen that an equivalent flow of a gas of higher density equates to a higher mass flow.

Given the same source conditions (source pressure, temperature and hole size) and assuming the discharge coefficient does not change, Equation (1) gives a mass flow for methane that is approximately a factor of 2.8 higher than that of hydrogen. The ratio will be approximately 3.2 for natural gas, depending on its actual composition. [Note for the purposes of this paper the mole composition has been assumed to be: Methane 88.4%, Ethane 5.5%, Nitrogen 2.5%, Propane 1.5%, n-Butane 0.5%, Carbon Dioxide 1.5%, n-Pentane 0.1%].

As the ratio of the densities of methane to hydrogen is approximately 8, the volumetric release rate of hydrogen is about by 8 / 2.8 = 2.9 more than that of methane. As the orifice size is a constant, the initial hydrogen gas velocities will also be higher by this factor. The momentum (mass flow rate x gas velocity) of the gas as it is released is therefore essentially the same for hydrogen and methane.

The time dependent behaviour for the release of a fixed inventory of gas is a little more complex. For example, Equation (1) has been used to calculate the outflow of methane and hydrogen gas from a 20m length of 52” pipe (vessel volume 27.4m^3) through a 20mm diameter hole, with an initial pressure and temperature of 150bara and 300K respectively. Figure 1 shows the time dependent properties as the contents of the vessel are released.

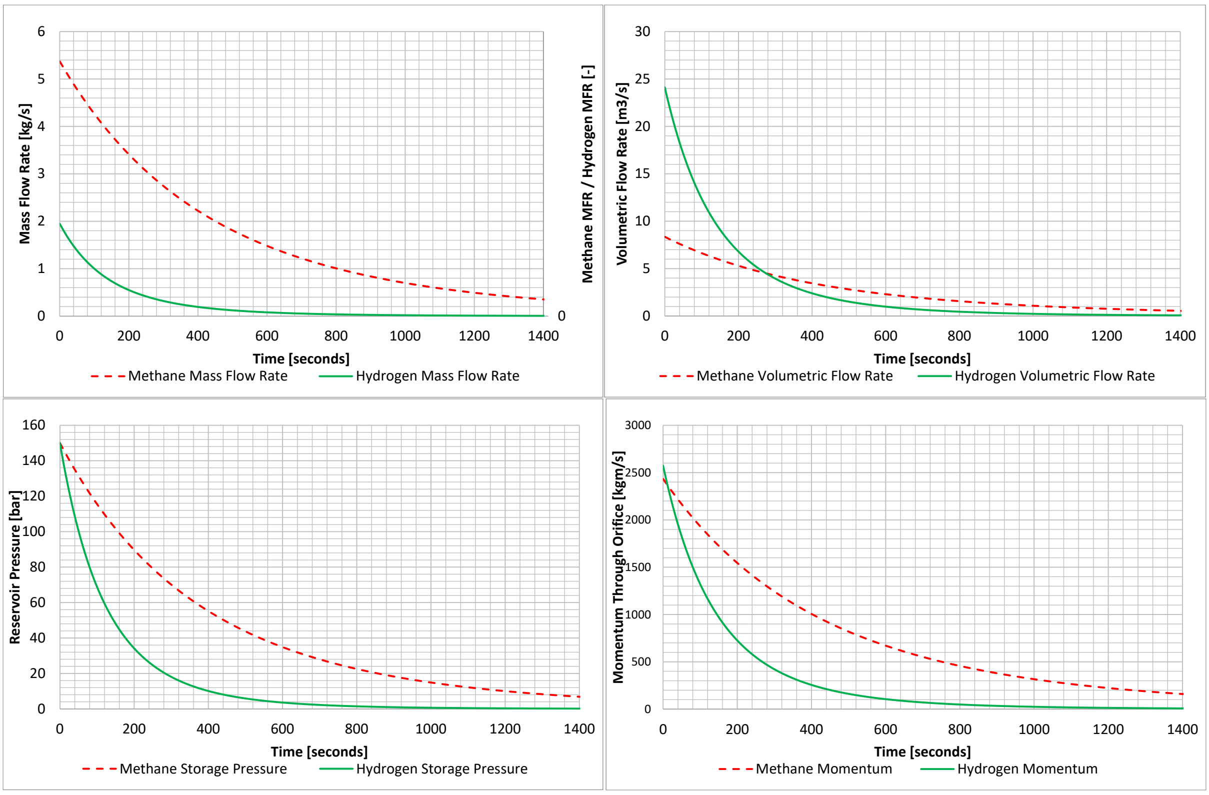

Figure 1: Vessel and release properties for hydrogen and methane (mass release rate – top left, volumetric flow – top right, vessel pressure – bottom left and release momentum – bottom right)

As discussed, the ratio of the initial mass flow rates of methane and hydrogen is 2.8:1. However, as the release progresses, this ratio increases, being about 10:1 after about 6 minutes and then continues to rise further (Figure 1 – top left). This rise happens because the volumetric flow of hydrogen is higher than for methane (Figure 1 – top right) and the pressure in the vessel therefore falls much quicker for hydrogen compared to methane (Figure 1 – bottom left). The consequence of this is that though the initial release momentum is about the same, the hydrogen case decays much faster than the methane case (Figure 1 – bottom right) and the release conditions will deviate more as time progresses.

Thus, for the same system pressure, volume and orifice size, the representative duration of a hydrogen jet fire will be nearly a third of that of a methane jet fire once isolation of the pressurised system has been achieved.

Energy Flow

The heat of combustion, not including the latent heat produced by water vapour condensation, of methane and hydrogen is 50 and 120 MJ/kg respectively. The power of a jet fire is given by:

$$Power = mass\ flow\ rate \times heat\ of\ combustion \quad (2)$$

Multiplying the higher mass flow rate of the methane release by the lower heat of combustion, provides an outflow power that is quite similar to that of hydrogen – the outflow power of hydrogen being about 85% of the methane power. The combustion energy available from a hydrogen release is therefore slightly less than that from a methane release under the same release conditions. The ratio between hydrogen and natural gas could vary slightly from the 0.85 factor for methane given that higher hydrocarbons give about 5% less heat of combustion compared to methane and there will also be inert gases present.

Again, though the initial powers are similar, for the transient release assessed in the previous section, the hydrogen power decreases much quicker than the methane case (Figure 2).

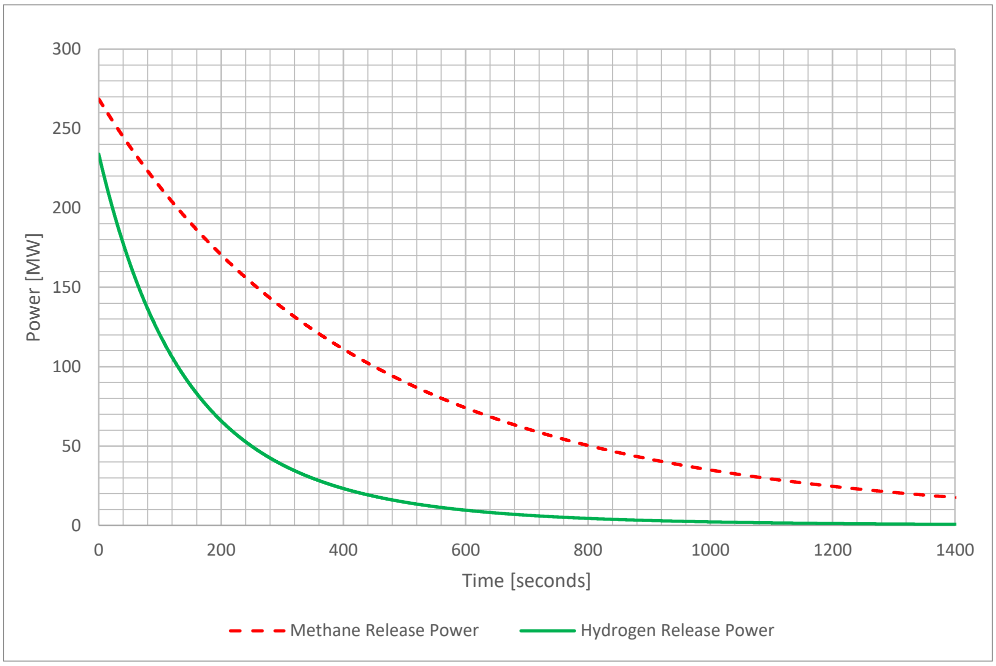

Figure 2: Release power variation with time

External Flame Characteristics

Flame Length

Most jet fire experiments with hydrogen have been conducted at 'small' scale, however as described earlier there is some limited data available from larger scale hydrogen tests. There is a substantial amount of large scale data available for natural gas and other hydrocarbon jet fires. It should be noted that flame lengths are somewhat dependent on whether the release is vertical or horizontal, however this factor is not considered here.

Figure 3 and Figure 4 show data from a range of jet fire tests plotted against mass release rate and jet flame power (combustion energy) respectively. In addition to the hydrocarbon data plotted, some pure hydrogen and natural gas/hydrogen mixture tests have been plotted on these graphs. All of the data used is in the public domain and has been taken from the references shown in the figure – either from tables or extracting data from plots using an online data extraction tool called WebPlotDigitizer. The "Schefer" correlations in the figures have been inferred from extracting data from the mass flow rate vs time, and flame length vs time plots in Schefer 2006, and Schefer 2007 and then plotting flame length against mass flow rate.

The hydrocarbon data correlates equally well on the basis of mass or power. However, the large scale hydrogen data, obtained from two experiments conducted at DNV Spadeadam Research & Testing with mass release rates of 1kg/s and 7.5kg/s (Rian 2019), fit within the spread of hydrocarbon data when plotted by jet flame power, but sit above the hydrocarbon data compared based on mass release rate. This indicates that the jet flame power is a better means of comparing hydrogen and methane/natural gas jet fires than mass flow.

An empirical line of best fit has been included in the jet flame power figure. The curve fit has been applied to all of the datapoints on the graph (so does not include the Schefer 2006 or the Schefer 2007 correlations). The line of best fit is:

$$L = 1.72\,(\text{Power})^{0.452} \qquad (3)$$

Also shown is the correlation published in FABIG TN13 2014. Either curve fits the data well in the 100MW jet fire to 5GW jet fire where most of the large scale data is present, but the new correlation is better when the smaller scale hydrogen data is also considered. What is most important in these graphs is that when the overall power of a jet fire release is similar for hydrogen and methane/natural gas jet flames, the jet fire flame lengths will also be similar.

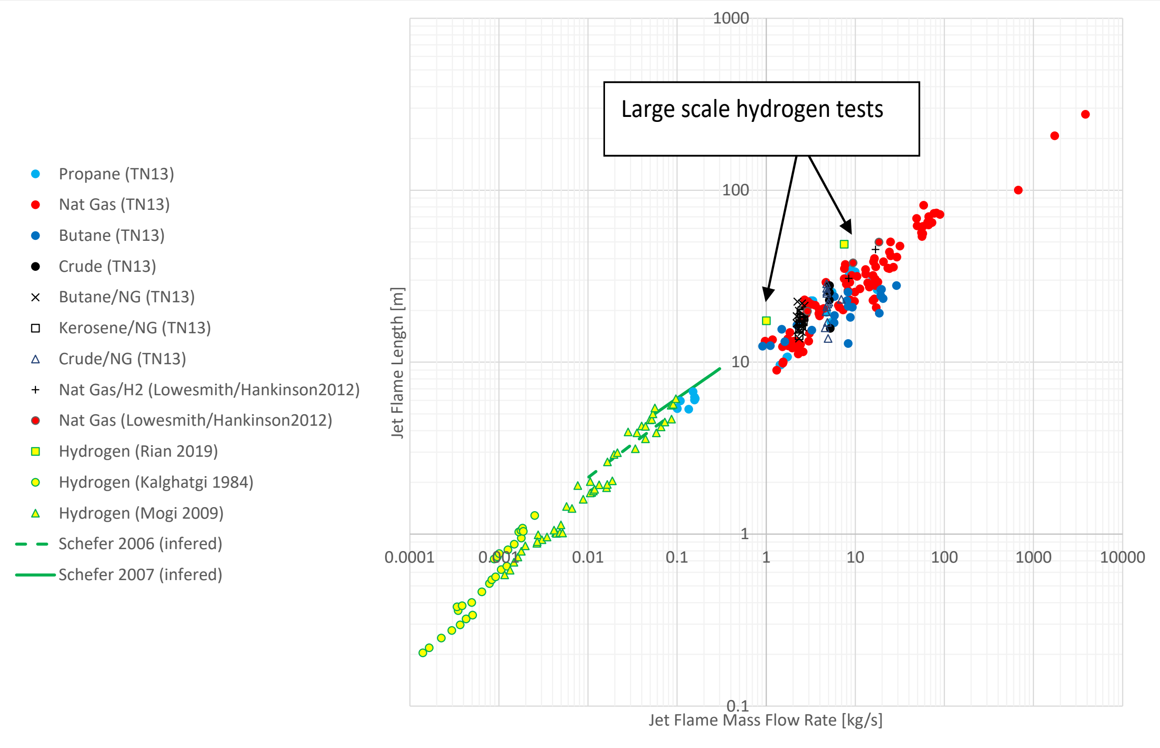

Figure 3: Flame length plotted against mass release rate

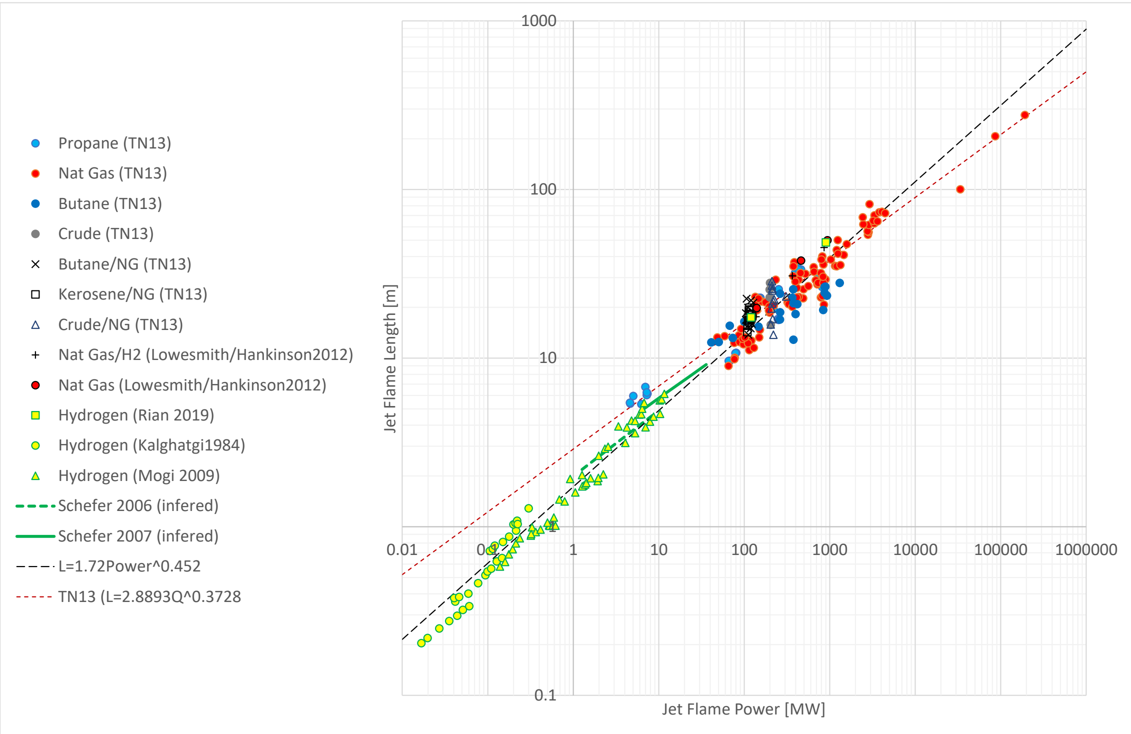

Figure 4: Flame length plotted against jet fire power

However, though initial flame lengths are similar the hydrogen flame length will decrease faster than that for methane due to the higher volumetric release rates for hydrogen, as shown in Figure 5, which uses the best fit correlation of flame length to power (including hydrogen data) in order to estimate the flame length.

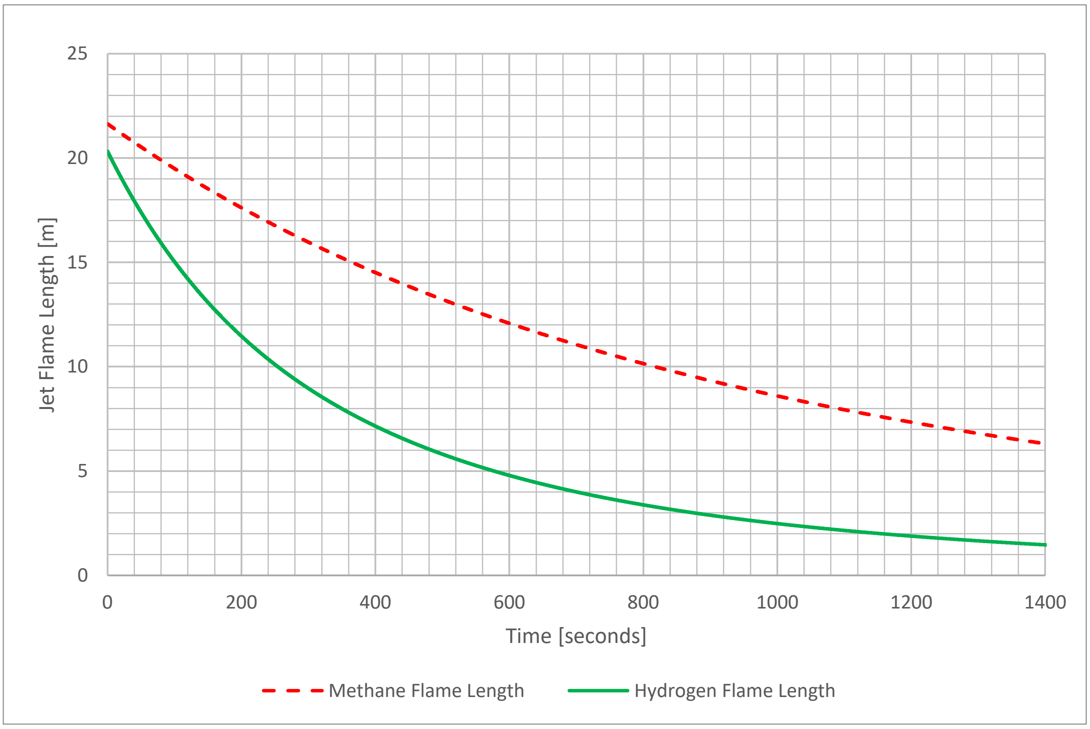

Figure 5: Flame lengths

Considering more complex flame modelling, Rian 2019 used the CFD code KFX to predict the temperature iso-contours of the two hydrogen jet fires conducted at DNV Spadeadam Research & Testing. In the experiments the flame length was estimated at 17.4m and 48.5m for the 1kg/s and 7.5kg/s tests respectively (120MW and 900MW release powers). The iso-contours for the KFX prediction for the two tests are shown in Figure 6, suggesting some underprediction of the flame length, though it should be noted that flame length for a horizontal jet fire should be measured along the centreline of the flame, not the horizontal extent.

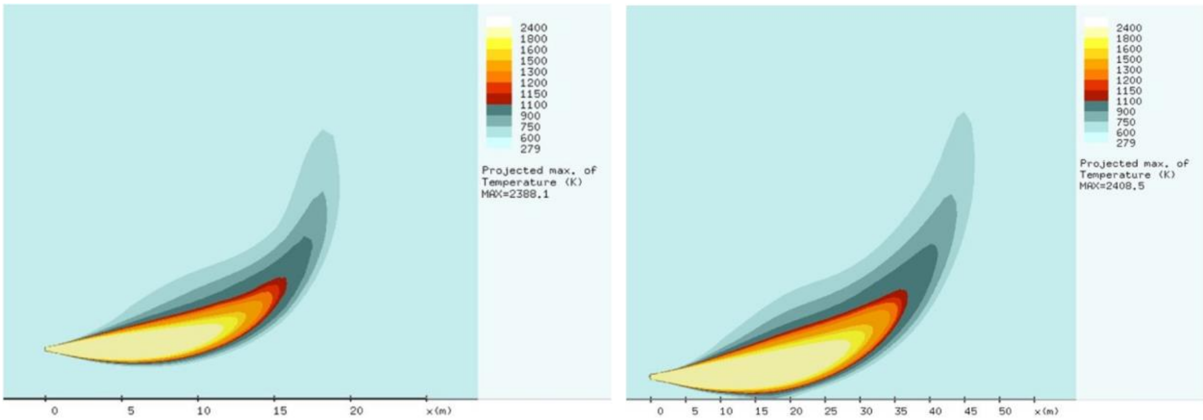

Figure 6: Temperature Iso-contours for KFX prediction of 1kg/s hydrogen jet fire (Rian 2019)

It is worth noting that given the release powers of these two tests are 120MW and 900MW, using the correlation derived from experimental data indicates flame lengths of 15m and 37.2m respectively. Given the uncertainties associated with the modelling and measurement of flame length, the agreement between the complex modelling, correlation and experimental results is very good.

Separate comparative calculations between hydrogen and natural gas have been carried out using the DNV jet fire model THRAIN and outflow model CORCE. A release pressure of 70barg was assumed through a 20mm orifice with a discharge coefficient of 0.86. The respective mass flows calculated for hydrogen and natural gas were 1.19kg/s and 3.85kg/s. As identified earlier, the mass flow rate of natural gas is 3.2 times higher than hydrogen, greater than the factor of 2.9 calculated for methane vs hydrogen due to the presence of higher hydrocarbon and inert gas components of natural gas.

Given the combustion energy of the assumed natural gas composition is 45.8MJ/kg, the release powers are 143MW for hydrogen and 176MW for natural gas. The correlation of flame length with release power indicates that the flame length for hydrogen would be about 9% less than that from the natural gas release. The flame length (defined by the point at which the temperature drops below 1400K) calculated by THRAIN is 19.4m and 22m for hydrogen and natural gas respectively for the case modelled, a drop of about 12% from natural gas to hydrogen, again indicating good agreement between the modelling and experimental data. It is notable that the hydrogen release rate is only slightly greater than the 1kg/s hydrogen experiment conducted at Spadeadam. The predicted flame length of 19.5m for a 143MW (1.19kg/s) hydrogen release is therefore very consistent with the measured flame length of 17.4m for a 120MW (1kg/s) hydrogen release.

In summary, experimental correlations and modelling using CFD and integral models indicate that hydrogen flame length correlates with combustion energy in the same way (within the inherent uncertainties) as a methane/natural gas flame length and that in a like for like release scenario in terms of hole size and release pressure, there are only marginal differences (~10%) in the flame length between hydrogen and natural gas/methane.

Flame Stability

As stated earlier, choked flow passes through the orifice at sonic velocity and higher than ambient pressure. Once in the ambient atmosphere the flow expands forming what is often referred to as a ‘pseudo’ or ‘notional’ orifice a short distance downstream of the actual physical orifice. This is described in Birch 1984.

Not all sonic releases can form a stable flame, there being a minimum physical orifice size required for the flame to stabilise on the gas jet. For example, see Kalghatgi 1984. At higher release pressures, this minimum release orifice reduces, and a larger proportion of release conditions produce stable flames. Stabilised flames are lifted off (displaced downstream) by some distance from the release point.

Due to their differing properties, lift off distance and flame stability will be different for a hydrogen jet fire compared to methane or natural gas. The lift off distance of a hydrogen jet fire is less than for the equivalent natural gas jet fire and the flame will be stable across a wider range of release sizes and pressures.

Fraction of Heat Radiated

For natural gas jet fires, the presence of carbon assists in increasing the proportion of heat that is radiated. In addition, the fraction of heat radiated increases as the mass release rate increases. For example the FABIG TN13 2014 guidance gives fractions of release power radiated as 0.08 and 0.13 for mass flow rates of 1kg/s and 10kg/s respectively.

Though hydrogen jet fires do not have the presence of carbon to aid thermal radiation, the fraction of heat radiated appears to be comparable to that for natural gas for similar sized jet fires. The 1kg/s and 7.5kg/s hydrogen jet fires (which equate to natural gas jet fires of about 3kg/s and 22.5kg/s) had quoted fractions of heat radiated of 0.12 and 0.19. KFX modelling in the same paper suggested fractions of heat radiated of 0.147 and 0.176 respectively for the two tests. It is notable that the KFX simulations generally achieved good agreement with the radiometer measurements made in these experiments (mean underprediction <10%).

Other sources in the literature suggest lower fractions of heat radiated, but also that the fraction increases with mass release rate, Schefer 2006 and Schefer 2007. However, they also state that the fraction of heat radiated by a hydrogen jet fire is lower than that from a hydrocarbon jet fire by a factor of two. Proust 2011 describes the fraction of energy radiated as heat being roughly between 0.1 and 0.15 on 2 mm and 3 mm orifices at flow rates up to 160 g/s. Overall, there does not appear to be any clear evidence that the fraction of heat radiated is markedly different compared to a natural gas jet fire at the same pressure and through the same hole size, though given the limited amount of large scale hydrogen data, there remains some uncertainty.

Internal Flame Characteristics

Flame Temperature

The adiabatic flame temperature for hydrogen is higher than that for methane by approximately 300K. This difference is also reflected in the flame temperatures predicted THRAIN and Figure 7 shows the predicted temperatures along the flame centreline, with temperature up to 1900K occurring in the hydrogen jet fire, whereas the maximum in the natural gas jet is 1735K. The maximum flame temperature in the KFX predictions shown in Figure 6 are approximately 2400K, which is close to the adiabatic flame temperature.

Flame temperature measurements are difficult to achieve accurately, at least in part due to the thermocouple losing energy to the surroundings by radiation. Nevertheless, Mogi 2019 describes thermocouples in a hydrogen fire plume achieving 1800K, and Proust 2011 1673K.

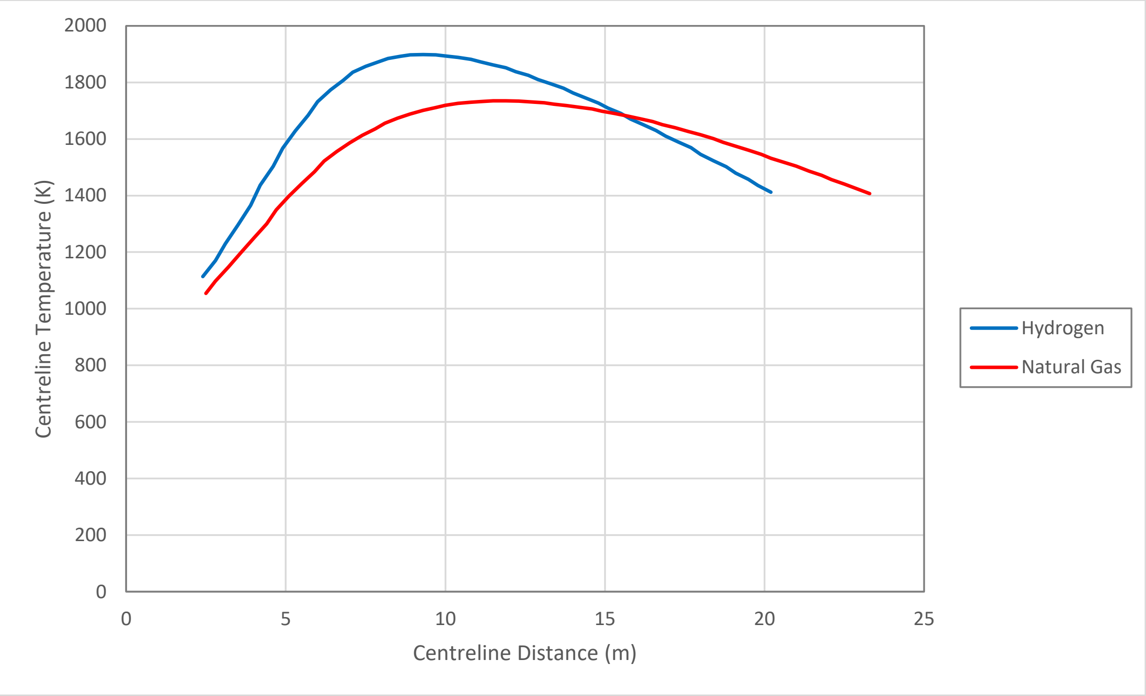

Figure 7: Predicted temperatures (THRAIN) on flame centreline for 70barg release through a 20mm diameter hole.

<u>Gas Velocities and Densities</u>

At the point of release, the hydrogen gas velocities will be significantly greater than an equivalent methane/natural gas. However, the velocities will reduce as air is entrained into the jet.

Figure 8 shows the gas densities and gas velocities predicted by THRAIN along the flame centreline. The densities in the hydrogen jet are slightly lower than in the natural gas jet flame at 2-3m from the release point. A short distance further out, they change to be higher.

The fact that the densities are similar indicates that a significant amount of air has already been entrained into the jet at a distance of 2-3m from the release point. The velocities for the hydrogen jet are predicted to be slightly below those in the natural gas jet.

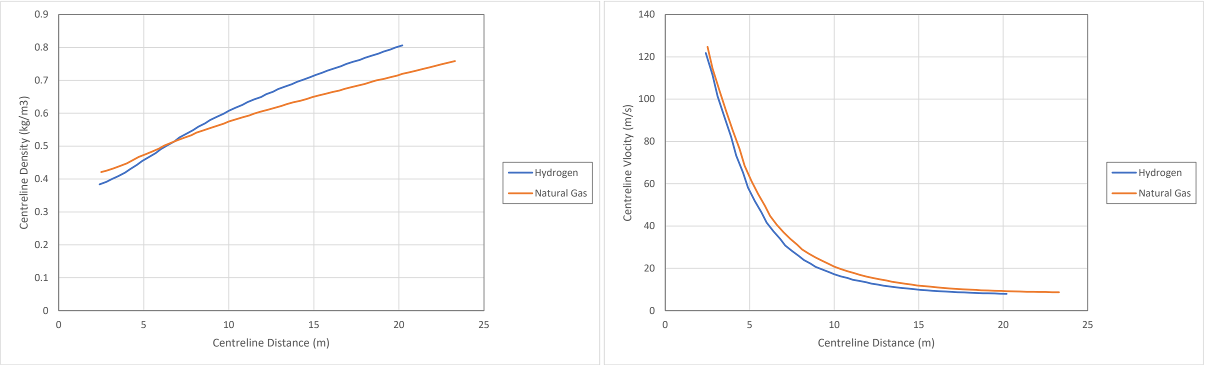

Figure 8: Predicted gas densities and velocities along the flame centreline (THRAIN, 70barg, 20mm hole)

Overall, this suggests the contribution to erosive forces provided by high velocity flow (drag) will not be significantly different between hydrogen and natural gas given sufficient separation from the release point. However, this has not been confirmed experimentally.

<u>Total Thermal Flux</u>

No measurement of thermal flux was made in the large scale hydrogen jets fires conducted at DNV Spadeadam previously and as a result there is no direct measurement of the convective and radiative components of the thermal flux to items within a hydrogen jet fire.

It might be expected that with a higher flame temperature and similar velocities in the jet, the convective thermal flux is higher in a hydrogen jet fire in some parts of the flame compared to that in a methane/natural gas jet fires. However, in the absence of any experimental measurement this remains an area of uncertainty.

Higher Pressures

It has already been shown that in a like-for-like release from a limited inventory, a hydrogen jet fire will have about one third of the duration compared to a methane/natural gas jet fire.

Some of the applications of hydrogen will be similar in terms of pressures and inventories as those for natural gas, for example distribution of hydrogen through gas transmission and distribution networks. However, it is recognised that gaseous hydrogen is often stored at pressures higher than that typically present in hydrocarbon process systems, such as in hydrogen refuelling stations for vehicles.

Hydrogen is routinely stored at higher pressures compared to natural gas, pressures of 700-800bar are not unusual. It is noted that high pressures also occur with hydrocarbons, but probably less frequently. If releases at these very high pressures follow a similar behaviour to the lower pressure releases already discussed, then they will correlate with flame power. In this case a very high pressure release through a smaller hole size can equate to a lower pressure release through a hole increased in size to give the same power, though it is possible that conditions very close to the release point may vary. This is an area lacking in any large scale experimental validation, particularly as the very high pressures may result in jet flame powers that exceed the range of current hydrocarbon jet fire data.

Potential Impact on Passive Fire Protection and Adequacy of Testing

PFP Jet Fire Testing

The Standard Jet Fire Resistance Test documented as ISO 22899-1 is a 0.3kg/s gaseous propane release located 1m away from and impacting at right angles on a plane surface inside a 1.5m square steel flame recirculation chamber, 0.5m deep. A PFP sample is placed in front of or inside the box depending on the equipment type being tested. The test is intended to simulate a 3kg/s natural gas jet fire impacting a receiver located 9m away from the gas release point where the total heat flux density was measured at around 300kW/m^2 of which about 50% was thermal radiation. In the ISO 22899-1 standard test the propane flame is deflected by the impact and sides of the box so that the flame radiation is emitted back to the test sample with the result that radiation flux densities are similar to that of the larger natural gas fire. Flame temperatures have been measured in the region 1370C to 1470K.

In the ISO22899-1 jet fire test, the impact zone of the propane release is predominantly unburnt gas and is relatively cold due to the distance between the release nozzle and the target. A short distance away from the impact zone the gases are fully combusted.

Due to concerns that there was potential for fire events generate heat fluxes greater than 300kW/m^2, from events such as high pressure releases from HP/HT wells, a high heat flux test has been developed to simulate heat fluxes of 350kW/m^2. While there is no international standard for the high heat flux test, commercial laboratories do undertake the test and generate the increased heat flux by increasing the depth of the flame recirculation chamber in the ISO 22899-1 standard test. Flame temperatures for this test are reported to reach in excess of 1470K. [Note there are other high heat flux tests available but the most common is that described above and for the purposes of this paper, this the high heat flux test will refer to this test configuration].

Types of PFP System

There are many different passive fire protective systems available and it is not the intent of this paper to discuss the different types in detail. This section refers to two broad categories, reactive and non-reactive systems. Reactive systems have been defined as systems where the heat of the flame causes a reaction within the coating that forms a protective layer reducing the conduction of heat to the substrate. An example is an intumescent PFP system where the heat from the flame results in the formation of a protective char. In a non-reactive coating there is no reaction to the heat of the flame with the product providing the insulation it its normal form. Examples are flexible jacket systems or steel clad insulated enclosures.

External Flame Characteristics

The assessment indicates that the fraction of heat radiated for hydrogen and natural gas jet fires is similar, suggesting that PFP response will be comparable in areas that are not impinged by high velocity flow. The standard jet fire test aims to maintain the radiative component of the heat flux and in that context should provide a suitable test for hydrogen releases. Similarly, the high heat flux test is based on an increased radiative component of the total heat flux.

Internal Flame Characteristics

The flame temperature of a hydrogen jet fire is of the order 1900K (1627C), potentially more, compared to 1735K (1462C) for the natural gas jet fire, a difference of 165 degrees. However, KFX predictions suggest that the hydrogen jet fire could reach significantly higher peak values. The higher potential flame temperatures in hydrogen jet fires are above those in the ISO22899-1 standard jet fire and high heat flux jet fire tests. The high flame temperatures are most likely of significance for reactive PFP coatings such as intumescent coatings. In the ISO 22899-1 and HHF jet fire tests, the impact zone is relatively cold due to the short distance between the release nozzle and the target and is predominantly unburnt gas. For reactive coatings the cold unburnt core means little of the coating reacts, with minimal char formation for intumescent coatings, and minimal erosion. Away from the impact zone, gases are fully combusted and these hotter zones create greater reaction, and char formation. Thus, in ISO22899-1 and high heat flux testing, the areas of highest heat energy and highest impact forces do not concur.

This review has focussed on methane / natural gas and hydrogen. It has indicated that the momentum of comparable hydrogen jet fires and methane/natural gas jet fires are similar and suggested that while gas densities are different, the gas velocities are similar away from the release point. This would suggest similar erosive forces. However close to the release point, the gas velocity of hydrogen is greater than natural gas and greater again than propane – the fuel used in the ISO 22899 and HHF jet fire tests used to test passive fire protection materials. Hydrogen is expected to have a shorter flame stabilisation distance than either fuel. On the basis that a hydrogen jet flame is both hotter and potentially more fully developed at the point of impact then it is possible that a 'cold' zone will not occur. The outcome may be a concurrence of the hottest part of the flame with the highest impact forces, which in turn may lead to a reduction in PFP protection.

While this is likely to be the case for reactive coatings, it may not make as much a difference for non-reactive coatings PFP systems where erosion is less of an issue. However, there are numerous non-reactive systems and many comprise of one or more components. The success or failure of these systems in a jet fire often depends on the integrity of the outer layer and the fixings that hold it together. Hydrogen jet fires may be hotter than the ISO 22899 jet fire test and if that causes fixings to fail, then hot gases can pass through to the protected item and/or the high velocity flow can pull the protection system apart.

Duration

The duration of hydrogen jet fires in like for like conditions are considered to be about 1/3 less than comparable methane jet fires meaning that PFP damage in a representative jet fire scenario would likely be reduced. This suggests that the duration of current jet fire tests would be suitable for testing hydrogen releases.

High Pressure

The effect of having very high pressures can be considered as an issue of whether higher power jet fires result in increased thermal and erosive load on PFP. If the jet fire power is within the range of existing hydrocarbon data, then there is no evidence to indicate that the higher pressure will, on its own, have an effect on PFP performance. However, as discussed previously the combined impact of erosion and higher flame temperatures for hydrogen release may affect the performance of PFP. This effect is likely to be increased for high pressure releases and as hydrogen is often stored at high pressures this is an area for future consideration. While the high heat flux test has an increased radiative component, the erosive nature of the release is the same as the ISO22899-1 jet fire test. Work to better understand the thermodynamic and physical characteristics of a high pressure hydrogen release, and allow a comparison with a similar natural gas release, would provide information on the impact of PFP systems and also the adequacy of the standard tests for assessment of PFP systems.

Conclusions and Future Work

A comparison of the high pressure gaseous hydrogen releases and jet fires with natural gas and methane has been undertaken and shows that like-for-like the external flame characteristics (flame length, thermal radiation) are not significantly different. If the release is transient (i.e. from an isolated inventory) a hydrogen jet fire will have a duration of about one third of a like-for-like methane/natural gas jet fire due to the higher volumetric outflow in the case of hydrogen. Internal flame characteristics show hydrogen jet fire flame temperatures are greater than those in methane/natural gas jet fires and suggests that the convective thermal flux to an object in the flame may be higher in the case of hydrogen compared to methane/natural gas.

With respect to the possible effects on PFP materials, the main differences between methane and hydrocarbon jet fires that are likely to affect PFP performance, are increased flame temperature and the potential for higher erosion due to higher pressure at locations that are close to the release point. This combination may have a greater effect on the erosion of reactive PFP systems such as intumescent coatings, than may be seen in hydrocarbon jet fires.

The gaps in understanding relate to the properties within large scale hydrogen jet fires, particularly flame temperature and convective and total heat flux. Large scale experimental data is therefore needed from measurements within hydrogen jet fires to confirm (or not) equivalence to natural gas/methane jet fires and the relationship to the propane jet fires currently used to test PFP systems. Once measured in experiments, there is a need to assess whether this affects the performance of certain PFP materials and whether the current ISO 22899-1 and proposed High Heat Flux tests are sufficient to indicate likely PFP performance. Alongside this there is a need to define representative hydrogen jet fire scenarios for the various hydrogen applications to understand both the likely size and duration of such fires.

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